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Aerobots in Planetary Exploration

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INTRODUCTION

Traditionally planetary exploration uses traditionally landers and rovers for in situ measurements and orbiters for remote sensing. Landers and the first generation rovers can conduct studies of very limited areas of the planet – square meters for landers and square kilometers for rovers. The main driver for selection of landing sites is safety and the safest sites are usually flat and not scientifically interesting. Besides even the best imaging from the orbit can not guarantee an obstacle-free site needed for the safe landing.

Robotic balloons (Aerobots) may significantly change the future of *in situ* planetary exploration. Aerobots can be used to study eight solar system bodies with atmospheres Earth, Venus, Mars, Jupiter, Saturn, Uranus, Neptune and Saturn's moon Titan. Besides the Earth, Venus, Mars and Titan are the prime candidates.

Venus is the closest and the easiest planet for aerobots. The first planetary balloons were part of the highly successful Soviet-French-US VEGA mission in 1985 (Fig.1).

Fig.1. Vega balloon in flight test

On Venus, aerobots may serve as the scientific platforms for the in *situ* atmospheric measurement and for study of atmospheric circulation. They can be used to drop imaging and deep sounding probes at sites of interest and to acquire and relay high-rate imaging data. Balloon ascent from the surface is essential for a Venus surface sample return mission.

On Mars, aerobots can fill the gap in resolution/coverage between orbiters and rovers. Powered aerobots (airships) can make controlled global flights for high-resolution radar, visible, infrared, thermal, magnetic and neutron mapping; they can be used for deployment of network of surface stations. Tethered balloons could provide ultra high-resolution imaging of local areas for navigation of rovers and data relay to the main lander station. Solar-heated balloons could be used for as low atmospheric decelerators for low-speed landing. In the more distant future, airships could be used for human transportation.

On Titan, powered aerobots can perform long duration low-altitude global flight for surface mapping, *in situ* atmospheric measurements, deployment of landers and rovers for *in situ* surface studies.

One of attractive features of aerobots is a almost ideal vertical orientation and a capability of deployment of large-size (but light-weight) structures that can be used in many experiments to increase their resolution and sensitivity.

Aerobot technologies have become more mature in the recent years due to progress in development of envelope materials, and envelope design driven primarily by stratospheric applications. Technologies for deployment and inflation., navigation, control, communication and power are also developing rapidly in response to planetary applications.

BALLOON BASICS AND PLANETARY ENVIRONMENT

Any lighter-than-air (LTA) vehicle uses two thousand years-old Archimede law to keep afloat:

$$M=\rho V \tag{1}$$

where M is a floating mass (mass of balloon, gas and payload), V – volume of the inflated balloon, r – atmospheric density. The more dense is the atmosphere the less volume of buoyant gas (and aerobot shell) is needed to fly.

The second fundamental law for the LTA flight is the 250-years old law of the thermal gas expansion

$$V=V_0T/T_0 \text{ (at } P=P_a) \tag{2}$$

$$P=P_0T/T_0 \text{ (at } V=const) \tag{3}$$

where T and T_0 are initial and current temperatures of the buoyant gas, P_a and P – ambient pressure and pressure inside the balloon. Equations (2) and (3) discriminate two the most common balloon types: zero-pressure and super-pressure balloons. In zero-pressure balloons the pressure of gas at some point inside the balloon is equal to the ambient pressure; the balloon has openings through which the gas is vented during its expansion. The super-pressure balloons have closed volume and the pressure inside should always exceed the ambient pressure.

The zero-pressure balloons are less demanding for material strength and can be made of many light-weight films and impregnated fabrics. They need some expendables to keep afloat for a long time (ballast, buoyant gas, fuel for hot-air balloons or their combinations); it limits their use for the long-duration planetary balloon missions.

The super-pressure balloons must held the pressure variations caused by variations of temperature of the buoyant gas that is almost equal to the temperature of envelope and may be significantly different from the ambient temperature. It requires stronger materials with low permeability and improved technology of fabrication. Hundreds of superpressure balloons were flown in the Earth atmosphere; some of them lasted up to two years.

Three candidate planets have very different environments (see Table 1).

Table 1. Planetary environments.

	Venus	Mars	Titan	Earth
Acceleration of gravity, g's	0.9	0.37	0.16	1
Main atmospheric gas	CO_2	CO_2	N_2	N_2
Surface Temperature, K	735	230	92	290
Surface Pressure, atm	92	0.0067	1.4	1.0
Surface air density, kg/m3	64	0.015	4.9	1.2
Solar flux at the upper atmosphere, W/m2	3200	700	13	1300
Solar flux near the surface, W/m2	5	700	<1?	600
Altitude of tropopause, km	~65	11		17
Pressure at tropopause, mbar	97	2.7		90
Temperature at tropopause, K	240	190	?	220
Diurnal temperature variations near the surface, $\delta T/T$, %	<0.3	30-50	<1-2	<10
Winds at the tropopause, m/s	80-100	20-30	?	20-30
Winds in lower atmosphere, m/s	1-3	5-20	<3?	5-20

Deep atmosphere of Venus exhibits a broad variations of atmospheric parameters. The heat and pressure in the lower atmosphere strongly limit the lifetime of surface and near-surface vehicles: without nuclear-power driven refrigerators or high-temperature electronics the lifetime would be ~2-3 hrs. High-temperature materials with good gas barrier and strength properties are needed for near-the surface LTA vehicles. On the other hand, the environment of the higher troposphere is quite mild and comparable with the troposphere of the Earth. The region is the most favorable for the aerobot missions (VEGA balloons flew at 53 km at pressure 0.5 bar and temperature ~30C). The main difference is sulfuric acid clouds that cover 100% of Venus.

On Mars, low density of the atmosphere in combination with big thermal variations requires light-weight and strong materials for long-duration aerobotic missions - the combination that is not easy to obtain. Though the proven balloon materials could be used for the low payload mass aerobots, the composite materials, new balloon designs ("pumpkin" shape) and advanced fabrication technology (so called three-DL technology which is used for fabrication of the world race sails) are the most perspective to improve efficiency of the aerobotic missions. Martian troposphere is similar to atmospheres of Venus and Earth; this similarity provides the basis for the Earth stratospheric flights to test the Martian aerobot systems.

The combination of high density (for times bigger than on the Earth) with low gravity (1/6 of the Earth value) and low temperature contrasts makes the Titan almost ideal for long-duration aerobot mission aerobot missions. The balloon materials become stronger at the extreme cold temperature; the adhesives that remain non-brittle at these temperatures are required.
Table 2 shows the typical parameters of the aerobots to lift the payload 10 kg ; for sake of comparison the areal density of the balloon material is assumed to be ~ 20 g/m2 for all planets (VEGA balloon material was ~300 g/m2).

Table 2

	Venus, 1 km	Venus, 60 km	Mars, 5 km	Titan, 1 km	Earth, 1 km	Earth, 34 km
Atmospheric density, kg/m3	61.56	0.489	0.010	4.80	1.13	0.010
Temperature of atmosphere, C	454	-10	-51	-181	-2	-33
Payload mass, kg	10	10	10	10	10	10
Balloon diameter, m	0.72	3.70	20.65	1.73	2.83	21.41
Balloon volume, m3	0.2	26.5	4610	2.7	11.9	5140
Balloon mass, kg	0.84	1.79	31.6	1.02	1.37	33.9
Mass of buoyant gas (He), kg	1.16	1.25	4.46	1.97	1.94	7.44
Total floating mass, kg	12.0	13.0	46.1	13.0	13.4	51.4
Payload mass as percent of floating mass, %	83.4	76.5	21.6	77.1	75.2	19.5
Mass of entry vehicle, kg	36	39	138	39		

The atmospheric density dominates the balloon size: Mars aerobot requires over 150 times bigger balloon (in volume) than the Venus aerobot at 60 km and over 1500 times bigger than the Titan aerobot near the surface. A mass efficiency (ratio of payload mass to the total floating mass that includes mass of payload, balloon and buoyant gas) is 75-80% for the Venus and Titan aerobots (it was ~ 30% for Vega balloons) and only ~20% for the Mars aerobot. Use of hydrogen instead of helium for buoyant gas will increase the efficiency of the Mars aerobot to 24%; the most radical way is to use lighter envelope materials: with 12 g/m2 will increase the efficiency almost twice.

If the Venus and Titan aerobots can take a considerable mass growth (the balloon for the Venus Surface Sample Return mission should lift ~400 kg ascent vehicle) it is not the case for Mars: it is unlikely that the nearest future Martian aerobots can lift more than 20-30 kg of payload.

MISSION SCENARIOS. DEPLOYMENT AND INFLATION OF AEROBOTS

As all lander and rover missions have many common features the same is with aerobots. The most common mission scenario would be launch of an interplanetary bus with the aerobot system enclosed into an entry vehicle, cruise phase to the planet, targeting at selected area on the planet, separation of the entry vehicle, entry and deceleration in the atmosphere, deployment and inflation of the aerobot (Fig.2), release of the entry vehicle and ascend (or descend) to the floating altitude where the active phase of the aerobotic mission starts.

Fig.2. Aerial deployment and inflation concept

Though the launch of planetary balloons from the surface is probably doable the aerial deployment and inflation seems more mass efficient, common and natural. At the same time the deployment and inflation is the most critical and the less simulated part of the mission because of complexity of aerodynamic processes involved.

The feasibility of aerial deployment and inflation of balloons made of heavy materials was demonstrated in Vega balloon mission. JPL is conducting now the flight tests of a new configuration of the balloon system with a bottom inflation. In August 1998 we demonstrated successful deployment and inflation of 3-m diameter spherical balloon made 12.5 mk Mylar film over El Mirage dry lake in California; this material was 17 times lighter than material of the Vega balloon (Fig.3). The test was quite stressful for the balloon since a heavy test module ('40 kg) with inflation tanks and flight test controller was suspended.

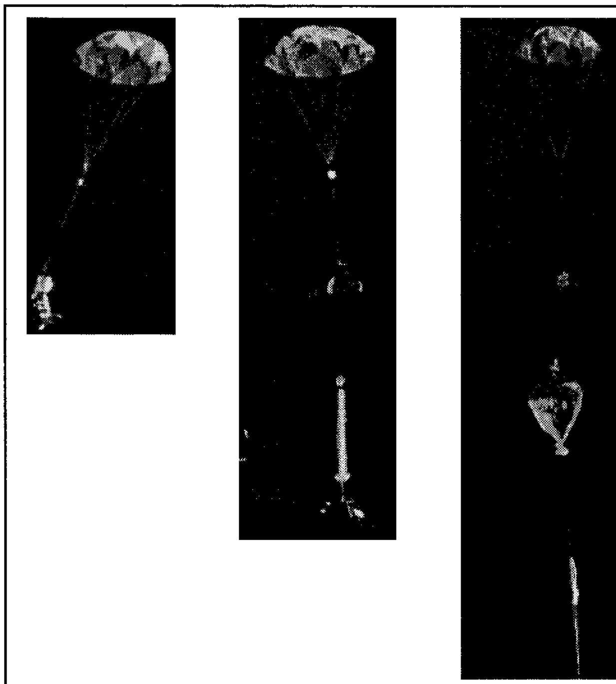

Fig.3. Tropospheric deployment and inflation test of 3-m Mylar balloon (August 21, 1998, El Mirage Dry Lake, California)

This test validated feasibility of the concept of aerial deployment and inflation of the modern thin-film balloons which is applicable to the Venus and Titan missions.

The deployment and inflation of Martian aerobot is even more challenging task since balloons are two order of magnitude larger (in volume), descent velocities during deployment are 10 times faster and balloon inflation should be completed very rapidly (usually in 150-250 sec) – to ensure that the balloon will start to rise before impact with the surface. Lack of successful demonstration of aerial deployment and inflation in the Russian-French Mars Aerostat project (1987-1995) shows the complexity of the problem.

Under the Cross Enterprise Technology Development Program JPL currently performs stratospheric tests of the full-scale prototypes of Martian balloons that should validate feasibility of aerial deployment (Fig.4) with the bottom inflation.

Fig.4. Launch of the flight train for the stratospheric test of aerial deployment and inflation (March 7, 1999, Hawaii)

The first results are encouraging – the system does not reveal a major aerodynamic instability which occurred in the Mars Aerostat test.

AEROBOT TRAJECTORIES

Unpowered aerobot moves with the wind and its trajectory will depend on average and instantaneous wind field. Trajectories of aerobots in the upper part of the Venus troposphere are quite predictable, at least on a several days span, since the winds are predominantly zonal, and directed clockwise. The Vega balloons that was inserted near the Venus equator drifted for two days with almost constant zonal velocity ~65 m/s and ~2 m/s in meridional direction. It is likely that the Titan which also a slowly rotating planet can have a similar wind pattern.

In the case of Mars which circulation pattern more likes the Earth's one the expected trajectories could be more random and will depend on the site, season and location of the entry point. Lack of predictability and of trajectory control is a weakness of unpowered aerobots. The vertical control of the aerobot may to some extent serve as a mean of horizontal control if the wind field is known - the examples are around-the-world balloon flights. Accuracy and control authority are limited with the knowledge of the current wind pattern and extent of possible controlled changes of the floating altitude. Fig. 5 shows examples the simulated Martian balloon trajectories.

Fig.5. Examples of simulated trajectories of unpowered Martian aerobots.

Planetary powered aerobots (airships) will provide capability of almost global and targeted access to any point that is below their floating altitude. For a long duration missions the power should be provided by non-expendable sources of energy - solar cells (Venus, Mars) or nuclear isotopes (Titan). The available power will determine a possible speed of powered aerobot. For the illustration the table 3 shows power requirements for aerobots with aerodynamic shape of the same diameter as in the table 1 for two speeds: 3 m/s and 15 m/s.

Table 3

	Venus, 1 km		Venus, 60 km		Mars, 5 km		Titan, 1 km	
Speed, m/s	3	15	3	15	3	15	3	15
Required thrust, N	22.5	560	4.7	118	3.0	75	10.1	254
Required electrical power, W	135	1600 0	28	3550	18	2260	61	7600

It was assumed that the drag coefficient is ~0.2 and efficiency of transformation from electrical to thrust power is ~50%.

The required power grows very rapidly – as cube of speed. For relatively small aerobots the available power can be of an order from tens to hundreds of watts and their air speed would be likely 3-7 m/s. It is not enough to fly upstream of 10-20 m/s winds but it is sufficient to steer across the wind to the desirable destination. Simulations show that even in the case of the Earth (which windfield is more variable than on the Mars, Venus or Titan) 2-4 m/s of horizontal control is enough to keep the balloon on a zonal trajectory.

Another application of powered aerobots could be in situ surface studies and sample collection. When winds in the lower atmosphere are small (as in case of Venus, Mars near the noon and likely Titan) the powered aerobot can hover above the selected site; the surface instrumented package can be winched down for the surface measurements or sample acquisition and winched up to the aerobot later. The aerobot serves as a flying rover but can cover much more sites than the traditional surface rovers.

COMMUNICATION

Aerobots can fly for tens of days and traverse tens and hundreds of thousands kilometers (the Vega balloons overflowed more than 11,000 km each just in two days) . They may fly in close vicinity to the surface and produce a huge amount of imaging, radar, spectroscopic, magnetic and other type of data with a resolution and coverage incomparable to any other scientific platforms. Capability of the space-to-Earth down link is the factor that will limit the data volume. Table 4 shows link budgets for direct-to-Earth link from the planetary aerobots using 0.5-m diameter antenna with 10 W X-band transmitter and the DSN 70-m antennas receiving stations.

Table 4.

	Venus, 1 km	**Venus, 60 km**	**Mars, 5 km**	**Titan, 1 km**
Range, mln km	130	130	400	1500
One-way light time, min	7.2	7.2	22.2	83.3
Planetary atmosphere absorption losses, dB	-8	-1	-0.1	-1
Ps/N0, dB-Hz	42.6	49.6	45.4	33.0
Bit rate, kbit/s	4.5	22.5	8.4	0.49
Average data volume, Mbit/day	16.2	972	362	21.2
Equivalent images/day	12.9	772.5	288.4	16.8

It was assumed that the average transmission lasts 12 hrs/day, each image is 1024x1024 pixels, 12 bits per pixel, and compression ratio 1:10. Transmission time for the Venus surface aerobot is assumed to be 1 hr.

The direct-to-Earth link can be provide adequate amount of data from the Venus aerobot at 60 km but not from the Venus surface or Titan aerobot. It is unlikely that the direct-to-Earth link with an articulated antenna and 10 W transmitter will be used on the Mars aerobot since the mass and power consumption of such system will take the most part of payload resources. The data relay via orbiter or fly-by spacecraft first used on the Soviet Venera-9 and Venera-10 missions in 1975 is the method to increase the data volume.

Building a communication relay infrastructure for Mars is the baseline of the Mars exploration program.
The recently developed Venus Aerobot Multisonde Mission concept (1) suggests to use the aerobot drifting at ~60 km to deploy surface imaging sondes at the designated locations, to receive high-rate imaging data from the sondes for further retransmission to the DSN via articulated antenna. The concept was proven partially on Steve's Fosset around-the-world balloon attempts in 1998 using Inmarsat-M module.

NAVIGATION

For unpowered aerobots the navigation is needed to locate the acquired data. For the powered aerobots the navigation is needed also for the trajectory control. Usual magnetic compass can not be used on Venus, Titan and Mars since none of them have significant magnetic field. A combination of sources can be used for navigation of the aerobots. Among them are: Doppler, range and VLBI measurements from the Earth, Doppler and Radio Direction Finding (RDF) measurements from the orbiter, on-board of aerobot measurements of direction to celestial sources – to the Sun (in optical and RF bands), to the Earth (RDF of DSN beacon), to the orbiter. The Martian moons Phobos and Deimos could be navigation sources for Martian aerobot. Surface recognition (images or altitude profiles) could be used to locate the aerobot position on Mars and Venus. IMU that is set up to the known position prior to the atmospheric entry can be used for navigation at the beginning of the atmospheric flight; it should be corrected regularly by exterior sources. The possible sources for on-board navigation are summarized in the Table 5.

Table 5

	Venus, 1 km	**Venus, 60 km**	**Mars, 5 km**	**Titan, 1 km**
Sun	In RF	In RF	In visible	In RF
Stars	No	No	In optical	No
Earth DSN in RF	Yes	Yes	Yes	Yes
Orbiter in RF	Yes	Yes	Yes	Yes
Moons of planet	No	No	Phobos, Deimos	No
Surface recognition	Altitude measurements	Altitude measurements	Optical, Altitude measurements	No
IMU	Yes	Yes	Yes	Yes

SUMMARY

Being a thousand times closer to the surface than the orbiter, covering thousands times larger surface area than traditional rovers and flying a thousand times longer than airplanes the aerobots can significantly influence future of the planetary exploration. Key technologies are existing or are in process of flight validation. Around-the-world flights around Venus, Titan and Mars can be accomplished in the close future.

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